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Final Report

HYBRID HARMONIC GYROTRON TRAVELING WAVE AMPLIFIER

AFOSR Grant ~~#AFOSR-90-0142A~~
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Contents

1 Executive Summary

This progress report summarizes the work done on the project "Hybrid Harmonic Gyrotron Traveling Wave Amplifier" covering the period from March 15, 1994 to October 31, 1994.

In the past seven and a half months, we have designed a compact harmonic multiplying gyro-TWT amplifier. The device is a three-stage tube with the output section running as an fourth harmonic gyro-TWT, the input section running as a fundamental gyro-TWT, and the middle section operating at the second harmonic of the cyclotron frequency. Radiation is suppressed by servers between the sections. The electron beam which drives the tube is produced by a magnetron injection gun (MIG). A TE_{0n} mode selective interaction circuit consisting of mode converters and a mode-filtering waveguide is employed for both input and output sections to solve the mode competition problem which is pervasive in overmoded gyro-TWT operation. The input section has an input coupler designed as a TE_{0n} mode launcher. It excites a signal at the fundamental cyclotron frequency (17.5 GHz), which is amplified in the first TWT interaction region. The bunched beam emerging from the first section has a frequency component at the second harmonic (35 GHz), which is amplified in the second section. Up to that point, the device is similar to a two-stage harmonic gyro-TWT. The distinction is that in the three-stage device the second section will be optimized not for output power but for fourth harmonic bunching of the beam. The beam then passes through a third TWT section which amplifies the fourth harmonic signal (70 GHz). The advantage of such a device is that the operating magnetic field is only 6.5 kilogauss, which may be realized with permanent magnets. A bandwidth larger than 10% is expected. Preliminary analysis indicates significant efficiency enhancement (by a factor >2) will result from this type of staged harmonic multiplication compared with an amplifier in which the penultimate stage operates at the fundamental of the electron cyclotron frequency.

The experimental work was included in an AFOSR contract entitled, "Harmonic Gyrotron Amplifiers and Phase-Locked Oscillators." Basic facilities for hot test of this gyro-TWT have been established and initially employed in a successful experimental study of phase-locking of a second harmonic gyrotron oscillator via a quasi-optical circulator. Cold test results of the vacuum compatible input coupler and the mode selective interaction circuit for the

fundamental prebunching section have been obtained. Single-mode, TE_{02} propagation has been confirmed using liquid crystal indicating that the realization of the hybrid gyro-TWT concepts is technically feasible.

2 Major Accomplishments to Date

This study is aimed at demonstrating the feasibility of a gyrotron amplifier operating at a higher harmonic of the electron cyclotron frequency for millimeter wave radar and advanced material processing applications. Accomplishments to date includes the following.

2.1 Completion of designs for 35 GHz and 70 GHz Gyro-TWTs

We have completed designs for a 35 GHz (two-stage) and a 70 GHz (three-stage) harmonic multiplying gyro-TWT. The operating mechanism of these devices is indicated in Fig. 1. The experimental work has been started with the two-stage gyrotron amplifier shown in Fig. 2 and 3. Table 1 shows the expected performance.

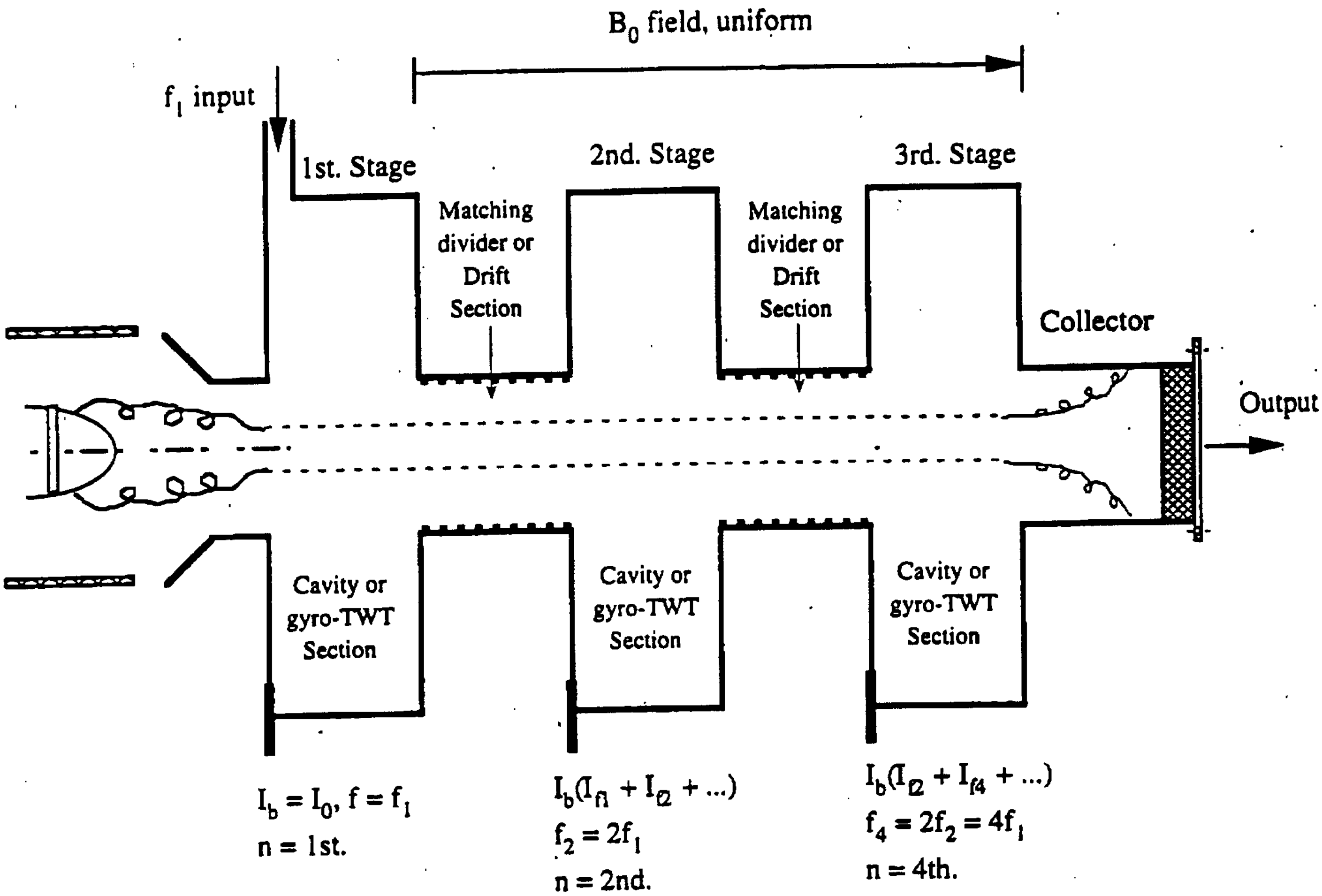
2.2 Cold tests

We have conducted cold tests of the vacuum compatible input coupler and the mode selective interaction circuit. Single-mode, TE_{02} propagation has been confirmed using liquid crystal as illustrated in Fig. 4.

2.3 Establishment of facilities for hot tests

We have established the basic facilities for hot test of the hybrid gyro-TWT and employed them in a successful experimental study of phase-locking of a second harmonic gyrotron oscillator via a quasi-optical circulator. A paper related to this achievement has been submitted to *IEEE Transactions on Plasma Science* for publication.

Fig.1 a **Physical Mechanism and Configuration of the Harmonic Multiplying Gyrotron**

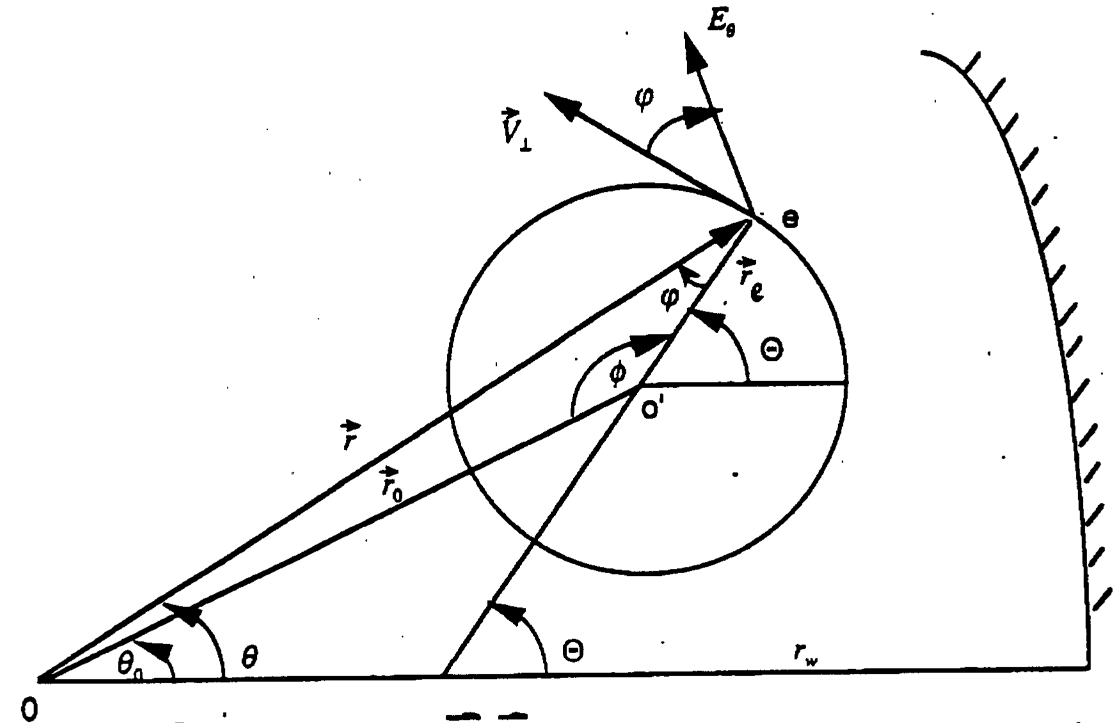


1st. stage:
- i) beam modulation by $V_{f1} \approx \int E^{(1)} d(r,\theta)$
- ii) fundamental ECRM interaction
- iii) $I_b = I_0 \rightarrow$ at the entrance

2nd. stage:
- i) $I_b = I_{f1} + I_{f2} + \ldots$ at the entrance and $f_2 = 2f_1$
- ii) $V_{f2} \approx \int E^{(2)} d(r,\theta)$ initiated by I_{f2}
- iii) second harmonic ECRM interaction
- iv) beam further modulated by V_{f2}

3rd. stage:
- i) $I_b \approx I_{f2} + I_{f4} + \ldots$ at the entrance and $f_4 = 2f_2 = 4f_1$
- ii) $V_{f4} \approx \int E^{(4)} d(r,\theta)$ initiated by I_{f4}
- iii) fourth harmonic ECRM interaction
- iv) $V_{f4} \rightarrow$ rf power

Fig.1 b **Synchronous E Field Interacting with the Electrons on the Orbit at mth Harmonic of the Cyclotron Frequency - E^m**



$$m_0c^2 \; d\gamma/dt = -e\,(\vec{V}\cdot\vec{E}_\theta) \tag{6}$$

$$d\gamma/dt = (e/m_0c^2)\, V_\perp\, E_\theta \cos\varphi \tag{7}$$

$$E_\Phi = E_\theta \cos\varphi$$

$$= E_0 J_1(K_c r)\sin(K_z z)\cos\omega t \cos\varphi \tag{8}$$

(for TE_{0n} mode)

According to Graf's formula of Bessel function

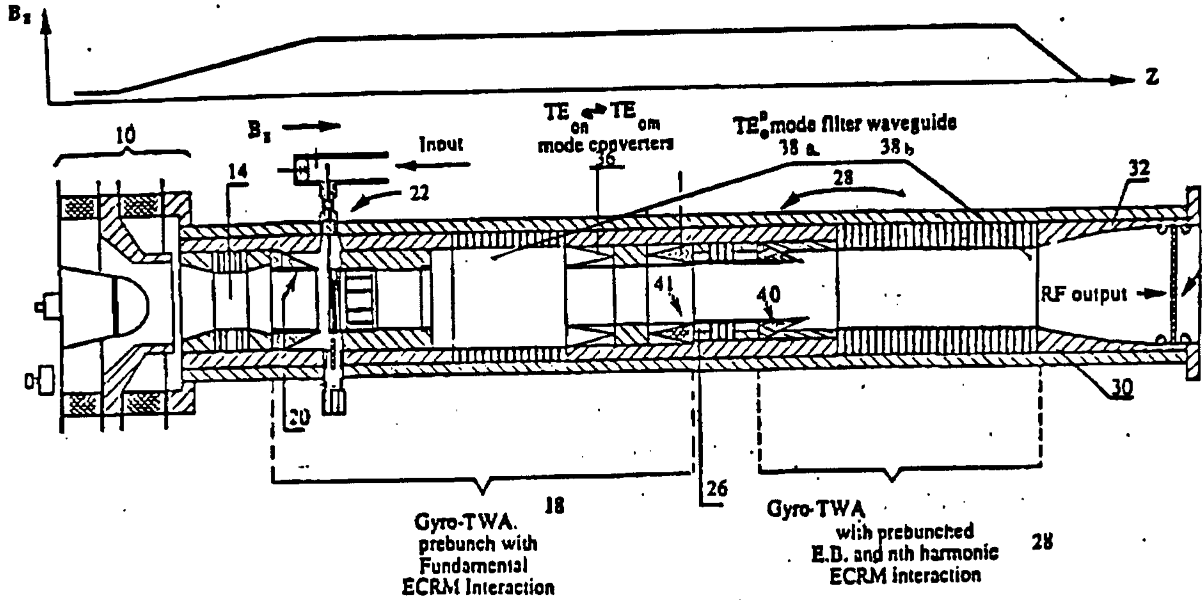
$$E_\phi = -E_0 \sum_{m=0}^{\infty} J_m(k_c r_0) J_m'(k_c r_e)\varepsilon_m \cos m\phi \sin(k_z z)\cos\omega t$$

$$= \sum_{m=0}^{\infty} E^m_{effect}\,\varepsilon_m \cos m\phi \sin(k_z z)\cos\omega t \tag{9}$$

$(\varepsilon_m = 1,\ m=0;\ \varepsilon_m = 2,\ m>0)$

$$E^m_{effect} = J_m(k_c r_0)\, J_m'(K_c r_e)(-E_0) \tag{10}$$

E^m_{effect} is the amplitude of mth cyclotron space harmonic of $E\phi$ experienced by electrons.



10. Magnetron injection electron gun
40,20. Taper matching load
26. Radiation-free divider
30. Output transition waveguide
32. Spent electron beam collector
38. TE^0_0 mode filter waveguide
18. First interaction section

14. Radiation suppressed beam tunnel
22. Input coupler/ TE_{om} mode launcher
36. $TE_{on} \rightleftharpoons TE_{om}$ mode converters
34. Broadband RF output window
41. Build-in matching load
28. Second interaction section

Fig.3 . **35 GHz frequency and harmonic multiplying gyro-TWT amplifier**

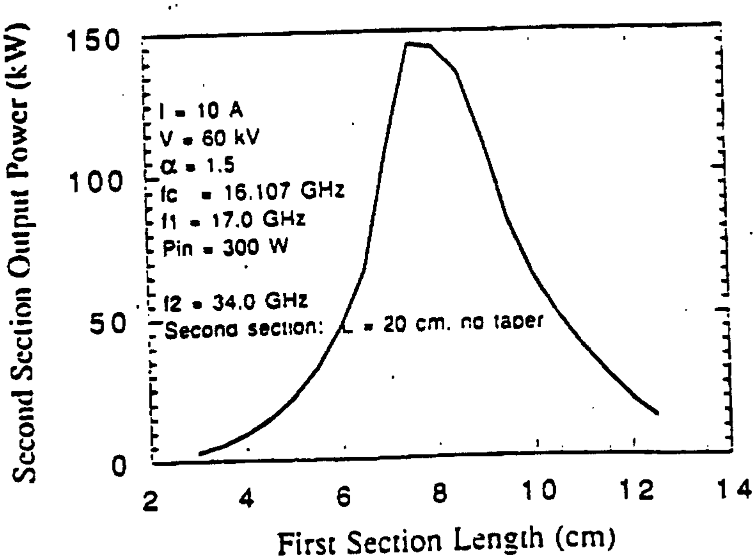
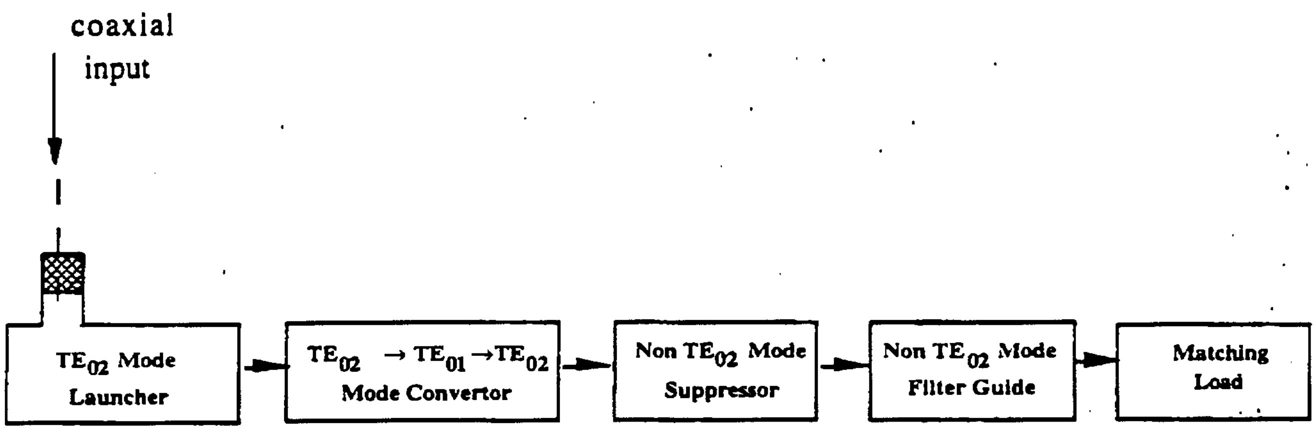


Fig. 2. Two-stage Gyro-TWA output power versus buncher section length.

Table 1. Expected performance of the 35 GHz, harmonic. multiplying, wideband gyro-TWT amplifier

Output center frequency	35 GHz
Instantaneous bandwidth	> 7 %
Output power	> 100 kW (peak), 1 kW (avg.)
Efficiency	> 20%
Gain	35 dB (linear), 26 dB (saturated)
Harmonic number	2 , 1
Output mode	TE_{03}
Magnetic field	6.5 kG (max.) compatible with modern permanent magnets (Ne/Fe/B)
Gun type	Magnetron Injection Gun
Gun voltage	60 kV
Gun current	9 A

Fig.4 **Cold Test Demonstration of a Mode Selective Gyro-TWT**



- **Transmission in TE_{02} mode observed in consistent with the theoretical pattern**

- **All components can be vacuum compatible**

- **With the potential of broadband operation**

- **With the capability to solve mode competition problems in gyro-TWT**

APPENDIX

Copies of Abstracts submitted to the
22nd IEEE International Conference on Plasma Science
June 5-8, 1995, Madison, WI

A. Phase-locking of a Second Harmonic Gyrotron Oscillator Using a Quasi-Optical Circulator to Separate Injection and Output Signals

B. Compact, Harmonic Multiplying Gyrotron Amplifiers

Phase-Locking of a Second-Harmonic Gyrotron Oscillator Using a Quasi-Optical Circulator to Separate Injection and Output Signals*

H.Z. Guo, D.J. Hoppe, J. Rodgers, R.M. Perez, J.P. Tate, MEMBER, IEEE, B.L. Conroy, V.L. Granatstein, FELLOW, IEEE, A. Bhanji, P.E. Latham, MEMBER, IEEE, G.S. Nusinovich, SENIOR MEMBER, IEEE, and M. Naiman

Phase-locking in a 34.5 GHz special complex cavity gyrotron oscillator operating at the second harmonic of the electron cyclotron frequency was studied. Injection of the locking power was made via a quasi-optical circulator connected to the gyrotron output waveguide. Locking bandwidth was measured both by instantaneous observation of a beat signal and by computer signal processing. Locking was observed with input power level as low as 40 dB below the gyrotron output power. The locking bandwidth is, however, narrower than in gyrotrons operating at the fundamental of the cyclotron frequency which may be attributed to the longer resonant cavity in the second harmonic gyrotron and the corresponding larger value of external quality factor. The measurements are roughly in agreement with predictions of a generalized Adler's phase-locking equation that allows for partial reflection of the injection signal at the entrance to the overcoupled gyrotron cavity.

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Compact, Harmonic Multiplying Gyrotron Amplifiers

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Abstract Submitted for the
22nd IEEE International Conference
on Plasma Science

June 5-8 1995
Madison, Wisconsin, USA

A compact, harmonic multiplying gyrotron traveling wave amplifier is being developed. The device is a three-stage tube with the output section running as a fourth harmonic gyro-TWT, the input section running as a fundamental gyro-TWT, and the middle operating at the second harmonic of the cyclotron frequency. Radiation is suppressed by servers between the sections. The operating beam of the tube is produced by a magnetron injection gun (MIG). A TE_{0n} mode selective interaction circuit consisting of mode converters and a filter waveguide is employed for both input and output sections to solve the mode competition problem, which is pervasive in gyro-TWT operation. The input section has an input coupler designed as a TE_{0n} mode launcher. It excites a signal at the fundamental cyclotron frequency (17.5 GHz), which is amplified in the first TWT interaction region. The bunched beam emerging from the first section has a frequency component at the second harmonic (35 GHz), which is amplified in the second section. So far the device is similar to a two-stage harmonic gyro-TWT. The distinction is that in the three-stage device the second section will be optimized not for output power but for fourth harmonic bunching of the beam. The beam then passes through a third TWT section which amplifies the fourth harmonic signal (70 GHz). The advantage of such a device is that the operating magnetic field is only 6.5 kilogauss, which may be realized with permanent magnets. A wide bandwidth larger than 10% is expected. Preliminary analysis indicates significant efficiency enhancement (by a factor >2) will result from this type of staged harmonic multiplication compared with an amplifier in which the penultimate stage operates at the fundamental of the electron cyclotron frequency. A gyroklystron amplifier has also been designed. The configuration is similar to the gyro-TWT but with the traveling wave interaction structures replaced by mode selective special complex cavities. Cold test results of the wideband input coupler and the TE_{0n} mode selective interaction circuit have been obtained. Single TE_{02} mode propagation has been confirmed using liquid crystal.

Work supported by the DoD Vacuum Electronics Initiative and managed by the Air Force Office of Scientific Research under grant AFOSR-91-0390 and by AFOSR under grant AFOSR-90-0142.

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